

**MODELING AND PERFORMANCE ANALYSIS
OF MOLECULAR COMMUNICATION
SYSTEMS**

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**BHARTI SCHOOL OF TELECOMMUNICATION
TECHNOLOGY AND MANAGEMENT
INDIAN INSTITUTE OF TECHNOLOGY DELHI
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OF MOLECULAR COMMUNICATION
SYSTEMS**

by

NILAY PANDEY

**BHARTI SCHOOL OF TELECOMMUNICATION
TECHNOLOGY AND MANAGEMENT**

Submitted

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to the



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We have not succeeded in answering all our problems. The answers we have found only serve to raise a whole set of new questions. In some ways we feel we are as confused as ever, but we believe we are confused on a higher level and about more important things.

Posted outside the mathematics reading room,

Tromsø University

Certificate

This is to certify that the thesis entitled “**Modeling and Performance Analysis of Molecular Communication Systems**” being submitted by **Mr. Nilay Pandey** to the Bharti School of Telecommunication Technology and Management, Indian Institute of Technology Delhi, for the award of the degree of **Doctor of Philosophy** is the record of the bona-fide research work carried out by him under our supervision. In our opinion, the thesis has reached the standards fulfilling the requirements of the regulations relating to the degree.

The results contained in this thesis have not been submitted either in part or in full to any other university or institute for the award of any degree or diploma.

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Nilay Pandey

Abstract

Recent advancements in the fields of biology and nanotechnology, have motivated scientists and engineers to create biologically inspired nanoscale devices called bio-nanomachines that are capable of interacting with biological systems at the nano and micro scale environments. Some of the envisioned applications of such bio-nanomachines include development and deployment of biohybrid systems, nanoscale sensors, targeted drug delivery, internet of nano-things, and body area networks. Using traditional electromagnetic communication at such scales is challenging and inefficient, necessitating the use of other communication paradigms. Of all the available options, molecular communication, where information is exchanged between the transmitter and the receiver through the exchange of information molecules, has emerged as the most promising one. Molecular communication is going to play a crucial role in the development of the internet of nano-things and related application areas. Therefore, in this thesis, we present a realistic and tractable analytical framework for analyzing a molecular communication channel and provide the performance analysis of such channels in terms of capacity and symbol error probability.

Most of the works in the existing literature have largely dealt with diffusion involving drift. Here, the noise term has an exponentially decaying tail similar to that of the Gaussian distribution. However, unlike these channels, the noise term in the case of molecular timing channels with pure diffusion belongs to the class of α -stable distributions which have stable tails. Some papers in the recent literature have tried to deal with this drift free channel and the stable nature of the Lévy distributed additive noise by considering a Lévy distribution with abrupt truncation, where the distribution just ceases to exist after a certain interval of time has elapsed. Although this approach does

allow a mathematical analysis of the drift free molecular timing channel, it is highly unrealistic and very difficult to achieve in practice. To overcome this, we adopt a more realistic exponential degradation model for information particles, which well models the natural decay of particles.

Apart from this, the problem of utilizing the channel diversity in case of molecular communication to improve its performance has not been studied in depth in the existing literature. We also propose use of the first arrival position information at the receiver to introduce diversity in the design of the molecular channels.

As molecular communication is envisaged to play a vital role in application areas such as biomedical, environmental, and manufacturing, it is beneficial to consider physically realistic molecular communication systems. This has motivated us to consider channels with turbulent flows also, as turbulent flows are highly prevalent in nature as well as engineering problems and to analyze such channels from a mobile molecular communication perspective. We consider a mobile molecular communication system where the fluid medium has a fully developed homogeneous turbulence, and both the transmit and the receive nano-devices are mobile. We derive its statistical properties like mean, correlation function, and distribution functions to fully characterize and describe this communication channel. We provide the performance analysis of these molecular communication channels and give novel closed form expressions for the channel statistics and the first arrival position density.

सार

जीव विज्ञान और नैनो प्रौद्योगिकी के क्षेत्र में हाल की प्रगति ने वैज्ञानिकों और इंजीनियरों को जैविक रूप से प्रेरित ऐसे नैनोस्केल डिवाइसेज़ और बायो मशीन बनाने के लिए प्रेरित किया है जोकि माइक्रो स्केल वातावरण में नैनो और जैविक प्रणालियों के साथ संवाद करने में सक्षम हैं। ऐसे जैव-नैनोमशीनों के प्रयोग क्षेत्र में टारगेट किए गए बायोहाईब्रिड सिस्टम, नैनोस्केल सेंसर का विकास और परिनियोजन, दवा वितरण, नैनो-चीजों का इंटरनेट और शरीर क्षेत्र नेटवर्क शामिल है। ऐसे पैमानों पर पारंपरिक विद्युत चुम्बकीय संचार का उपयोग करना चुनौतीपूर्ण और कठिन है, इसलिए अन्य संचार प्रतिमानों का उपयोग जरूरी है। सभी उपलब्ध विकल्पों में से, आणविक संचार, जहां ट्रांसमीटर और रिसीवर के बीच सूचना का आदान-प्रदान सूचना अणुओं के आदान-प्रदान के माध्यम से होता है, सबसे सटीक विकल्प के रूप में उभरा है। नैनो-चीजों और संबंधित अनुप्रयोग क्षेत्रों का इंटरनेट के विकास में आणविक संचार एक महत्वपूर्ण भूमिका निभाने जा रहा है। इसलिए, इस थीसिस में हमारा उद्देश्य है कि हम आणविक संचार चैनल का विश्लेषण करने के लिए एक व्यावहारिक और ट्रैक्टेबल विश्लेषणात्मक रूपरेखा प्रस्तुत करें और इस तरह के चैनलों के प्रदर्शन त्रुटि संभावना का विश्लेषण प्रदान करें।

मौजूदा साहित्य के अधिकांश कार्यों में काफी हद तक बहाव से जुड़े प्रसार से जुड़े हैं। यहाँ, गॉसियन डिस्ट्रीब्यूशन के समान ही शोर शब्द की एक क्षयकारी पूंछ होती है। हालांकि, इन चैनलों के विपरीत, शुद्ध प्रसार के साथ आणविक समय चैनलों के मामले में शोर शब्द α - स्थिर वितरण के वर्ग के अंतर्गत आता है जिसमें स्थिर पूंछ होती है। हाल के साहित्य में कुछ पत्रों ने इस बहाव-मुक्त चैनल से निपटने की कोशिश की है और लेवी की स्थिर प्रकृति ने अचानक ट्रंकेशन के साथ लेवी वितरण पर विचार करके अतिरिक्त शोर को वितरित किया, जहां वितरण सिर्फ समय के एक निश्चित अंतराल के बाद अस्तित्व समाप्त हो जाता है। यद्यपि यह दृष्टिकोण बहाव मुक्त आणविक समय चैनल के गणितीय विश्लेषण की अनुमति देता है, यह अत्यधिक है व्यवहार में अवास्तविक और बहुत कठिन है। इसे दूर करने के लिए हम एक और तरीका अपनाते हैं सूचना कणों के लिए यथार्थवादी घातीय गिरावट मॉडल, जो कणों का प्राकृतिक क्षय अच्छी तरह से मॉडल करता है।

इसके अलावा, आणविक संचार के प्रदर्शन में सुधार के लिए चैनल विविधता का उपयोग करने की समस्या का मौजूदा साहित्य में गहराई से अध्ययन नहीं किया गया है। हम आणविक चैनलों के डिजाइन में विविधता का परिचय देने के लिए रिसीवर पर पहले आगमन की स्थिति की जानकारी का उपयोग करने का भी प्रस्ताव करते हैं।

चूंकि आणविक संचार को जैव चिकित्सा, पर्यावरण और निर्माण जैसे अनुप्रयोग क्षेत्रों में एक महत्वपूर्ण भूमिका निभाने के लिए परिकल्पित किया गया है, इसलिए व्यावहारिक रूप से यथार्थवादी आणविक संचार प्रणालियों पर विचार करना फायदेमंद है। इसने हमें टर्बुलेन्स प्रवाह वाले चैनलों पर भी विचार करने के लिए प्रेरित किया है, क्योंकि टर्बुलेन्स प्रवाह प्रकृति के साथ-साथ इंजीनियरिंग समस्याओं में भी प्रचलित हैं और मोबाइल आणविक संचार परिप्रेक्ष्य से ऐसे चैनलों का विश्लेषण करना जरूरी है। हम एक मोबाइल आणविक संचार प्रणाली पर विचार करते हैं जहां द्रव माध्यम में एक पूर्ण विकसित सजातीय टर्बुलेन्स है, और ट्रांसमिट और रिसीवर नैनो-उपकरण दोनों मोबाइल हैं। हम इसके सांख्यिकीय गुणों जैसे कि माध्य, कोरेलेशन और डिस्ट्रीब्यूशन फंक्शन की गणना करते हैं ताकि इस संचार चैनल का वर्णन पूरी तरह से किया जा सके। हम इन आणविक संचार चैनलों का प्रदर्शन विश्लेषण प्रदान करते हैं और प्रथम आगमन स्थिति घनत्व के लिए नया बंद-प्रपत्र अभिव्यक्ति देते हैं।

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Abbreviations

ACF	Auto correlation function
AM	Amplitude modulation
BoN	Body area networks
CCDF	Complementary cumulative distribution function
CDF	Cumulative distribution function
CF	Characteristic function
CSK	Concentration shift keying
EM	Electromagnetic
FAP	First arrival position
FDT	Fully developed turbulence
FPT	First passage time
FRET	Förster resonance energy transfer
IG	Inverse Gaussian
iid	Independent and identically distributed
IoNT	Internet of nano things
MC	Molecular communication
ML	Maximum likelihood
PDF	Probability density function
RV	Random variable
SEP	Symbol error probability
TLD	Truncated Lévy distribution
TLF	Truncated Lévy flight